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Laboratory Measurements of Radiance and Reflectance Spectra of Dilute Primary-Treated Sewage Sludge

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and Space Administration

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SUMMARY

The National Aeronautics and Space Administration (NASA), in cooperation with the Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA), is conducting a research program to evaluate the feasibility of remotely monitoring ocean dumping of waste products such as acid and sewage sludge. One aspect of the research program involves the measurements of upwelled spectral signatures for sewage-sludge mixtures of different concentrations in a large-scale laboratory. This paper describes the laboratory arrangement, solar simulator, and test results from three experiments conducted in the laboratory. Radiance and reflectance spectra are presented for primary-treated sewage sludge mixed with two types of base water. Results indicate that upwelled reflectance varies in a near-linear manner with concentration and that the sludge has a practically flat signal response between 420 and 970 nm. Well-defined upwelled reflectance spectra were obtained for the sewage-sludge mixtures at all wavelengths and concentrations. The spectral reflectance values appeared to be influenced by the type of base water, but this influence was small, especially for the mixtures with low concentrations of sewage sludge.

INTRODUCTION

The National Aeronautics and Space Administration (NASA), in cooperation with the Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA), is conducting a research program to evaluate the feasibility of remotely monitoring ocean dumping of waste products such as acid and sewage sludge. Pollution of the marine environment from these and other products and its effects on the social and economic health of the public have become problems of national significance (refs. 1 and 2). For this reason, NASA devotes part of its resources to the research and development of remote sensing systems and to the application of these systems to the investigation of problems related to water quality (ref. 3). More specifically, one research program at the Langley Research Center (LaRC) involves conducting fundamental spectral signature studies and analytical studies related to pollutants in the marine environment. Some of these studies are directed toward evaluating the feasibility of remotely monitoring ocean dumping of wastes such as acid and sewage sludge (refs. 4 to 8).

Sewage sludge is routinely dumped into coastal zone waters in areas specifically designated for that purpose. Generally, these areas cover several square kilometers. The environmental factors which determine the ultimate fate of these materials, such as water and atmospheric dynamics, are not completely understood. Also, for various reasons, the dumping operations do not always occur in the designated zones, and the sewage may drift and contaminate beaches or areas rich in marine life. Because of the uncertainties in the ultimate fate of these materials, it is desirable to monitor these designated dump areas remotely and to be able to identify coastal zone waters which contain various concentrations of sewage sludge. To accomplish this remotely, the reflectance spectra of the material in the water at various concentrations are required.

Several airplane flights with multispectral scanners were made over sewage-sludge dump sites in the New York Bight (refs. 6 and 8) and the Atlantic Ocean off Cape Henlopen, Delaware. Also, small-scale laboratory investigations are being conducted to determine the composition and optical characteristics of the sewage sludge that produce the spectral signature of the material. In addition, reflectance spectra of sewage-sludge mixtures of different concentrations were measured in a spectral signature laboratory and this work is the subject of the present paper. The objectives of these experiments were

(1) To measure upwelled radiance and reflectance spectra of sewage sludge

(2) To measure these spectra at various concentration levels and to investigate the degree of linearity of the upwelled radiance with constituent concentration

(3) To assess the effects of base water and experimental repeatability

The upwelled spectral signature laboratory, as well as some of the components in the laboratory setup, is described in this paper. Results of three experiments conducted in October and November 1976 are presented.

To accomplish these objectives, primary-treated sewage sludge was mixed with two types of base water. Conditioned tap water was used for two experiments and water from Back River was used for the third experiment. (Back River is located in Hampton, Virginia, on the western side of the Chesapeake Bay and about 16 km from its mouth.) The sewage sludge was mixed with these two water types to obtain several concentrations. Upwelled radiance spectra were measured for the base water and each of these concentrations. Reflectance spectra were calculated from these data and approximations of the linearity of reflectance with concentration were made. Comparisons of the reflectance values from the two experiments conducted with conditioned tap water were made and reflectance values from one of these experiments were compared with values from the experiment conducted with natural water.

SYMBOLS

A	area of spectrometer entrance slit, cm^2
D	vertical displacement of oscilloscope measurement, cm
$E(\lambda)$	spectral irradiance, W/m^2-nm
K	ratio of instrument throughput to vertical-scale sensitivity factor, $13.7 \times 10^3 \frac{cm^2\text{-}sr}{mW/nm\text{-}cm}$
$L_u(\lambda)$	upwelled spectral radiance, $\frac{mW/nm}{cm^2\text{-}sr}$
$P(\lambda)$	spectral power, mW/nm
S	vertical-scale sensitivity factor, mW/cm-nm
λ	wavelength, nm
$\rho_c(\lambda)$	spectral reflectance, percent of input (relative to a 100-percent diffuse reflector)
Ω	acceptance solid angle of spectrometer, sr

LABORATORY AND EQUIPMENT

Figure 1 is a sketch of the laboratory arrangement. Major parts of the setup include a water tank, circulation system, filtration and deionization system, solar simulator, first-surface mirror, and rapid-scan spectrometer. A black canvas tent covers the water tank to block out background radiation during testing and to minimize the amount of contaminants, such as dust, entering the water tank.

The cylindrical steel water tank has a diameter of 2.5 m and a depth of 3 m. The bottom is concave as illustrated in figure 1. The tank interior is coated with a black phenolic paint that absorbs 97 percent of incident radiation. For these experiments, the tank was filled to within 0.3 m of the top with about 11 600 liters of water.

The circulation system was designed to maintain a vertical and horizontal homogeneous mixture in the tank and to maintain in suspension sediment particle sizes up

to 100 μm (Specific gravity = 2.6). This particle size corresponds to fine sand. To accomplish these design goals, water is pumped from the drain at the bottom of the tank into a system of pipes which returns the water to the tank through two vertical pipes on opposite sides of the interior of the tank: the water is emptied just above the concave bottom of the tank. Water entering the tank through these pipes washes over the concave bottom, meets at a location away from the drain, and wells upward. Tests using tracer techniques and transmission measurements have confirmed that this circulation system provides a uniform homogeneous mixture throughout the tank and keeps particles larger than fine sand in suspension. For pollutants such as sewage sludge with specific gravities of less than 2.6, the present laboratory setup will suspend particles that are much larger than 100 μm in diameter.

The filtration and deionization system includes a commercial fiber swimming-pool filter, an activated carbon filter, and a charged resin deionizer. These units are aligned with water lines parallel to the main circulation system water lines, and can be used separately or in any combination by the use of valves. The two filters remove suspended and organic materials from the water before it reaches the deionizer, where dissolved ionic substances are removed. Table I shows a comparison between water conditioned through this system and Back River water. Generally, after tap water is conditioned through this system, it contains less than 0.5 ppm of suspended solids and less than 2 ppm of dissolved substances. These results were obtained by analyzing water samples taken from the tank on several occasions. The data listed for Back River, however, were obtained by analyzing a sample of Back River water taken from the tank on November 4, 1976.

The light source is a solar radiation simulator designed to approximate the spectral content of the Sun's rays. The radiation spectrum is produced by a 2.5-kW xenon short-arc lamp and transmitted to the target plane through an optical arrangement inside the simulator and a collimating lens accessory. Without the collimating lens accessory, the simulator projects a beam of light, uniform in intensity and spectral content, on a 0.3-m-diameter plane surface located 0.61 m from the instrument. With the collimating lens accessory, the projected beam is collimated to a 0.15-m diameter 0.3 m from the instrument and has a $\pm 2.5^{\circ}$ collimation angle. For these experiments, the simulator was located approximately 15.2 m from the water tank as illustrated in figure 1. At this distance from the simulator, the beam is about 1.2 m in diameter. A mirror positioned 1.52 m above the water tank reflects the center of the beam to the water surface. The incidence angle with the water surface is 13°. The mirror is a first-surface mirror coated with aluminum and protected by an overcoat of silicon monoxide. It has a 0.3-m diameter and reflects an elliptical spot on the surface of the water which has a maximum diameter of 0.35 m. The simulator spectrum input to the water surface is similar to,

but not a precise duplicate of, sea-level standard solar-radiation curves often used in engineering calculations (ref. 9). Figure 2(a) shows that the standard sea-level curves are quite variable depending on the solar elevation angle. Figure 2(b) is the simulator spectrum normalized to the 30° solar spectrum at 600 nm. These curves suggest that, when laboratory measurements are made at a 32-nm spectral resolution, the input spectrum and possibly the output measurements are similar to those that would be expected in the field if the solar elevation angle was greater than about 30°. The total intensity of the light hitting the water surface is approximately 8 percent of that in the field.

The rapid-scanning spectrometer system consists of a spectrometer unit with a telephoto lens attachment and a plug-in unit with an oscilloscope and Polaroid camera attachment. The spectrometer unit with telephoto lens attachment is mounted 2.43 m above the surface of the water as illustrated in figure 1. The spectrometer uses a Czerny-Turner grating monochromator with no exit slit. The spectral output of the monochromator is focused on the target of a vidicon tube where the spectrum is stored as an electrical charge image. An electron beam periodically scans across the vidicon target, thereby converting the charge image into an electronic signal. This signal is processed by the plug-in unit which functions as an electronic signal processor and controller between the spectrometer and the oscilloscope. The signal is displayed on the oscilloscope and is photographically recorded by the camera. The spectrometer is designed to measure power per nanometer of spectral bandwidth. The oscilloscope screen is used to show displacement. The power per nanometer $P(\lambda)$ is proportional to displacement D as shown in the following equation:

$$P(\lambda) = DS \tag{1}$$

The vertical-scale sensitivity factor S is calibrated internally by the manufacturer and is displayed on the oscilloscope screen. The upwelled radiance per nanometer of spectral bandwidth $L_u(\lambda)$ is defined as

$$L_u(\lambda) = \frac{P(\lambda)}{A\Omega} \tag{2}$$

where A is the area of the spectrometer entrance slit and Ω is the acceptance solid angle of the instrument. The quantity $A\Omega$ is defined as the instrument throughput and is a measure of the capacity of a system to collect light. Combining equations (1) and (2) gives

$$L_u(\lambda) = \frac{DS}{A\Omega} \tag{3}$$

or

$$L_u(\lambda) = \frac{D}{K} \tag{4}$$

where

$$K = \frac{A\Omega}{S}$$

Thus, upwelled spectral radiance per nanometer is proportional to displacement, and the proportionality constant is a function of instrument calibration. For the tests described herein, the actual measured upwelled spectra are presented in terms of radiance or $L_u(\lambda)$.

EXPERIMENTAL METHOD

A series of three experiments was conducted to obtain upwelled radiance spectra for various concentrations of primary-treated sewage sludge in two types of base water. Samples of the sewage sludge were collected in thirty-two 1-gal containers from the Southwest Philadelphia Waste Treatment Facility on October 21, 1976. (1 gal = 0.004 m^3.) Table II shows typical results of a laboratory analysis of the sewage sludge from this treatment facility. However, no similar analysis was made of the samples used in the present experiments. Usually, this material is carried by barge about 65 km offshore of the entrance to Delaware Bay and dumped into the Atlantic Ocean. These samples were transported on ice in coolers to LaRC and kept under refrigeration at 4^{o} C until the experiments were conducted. Before each experiment, determinations of total suspended solids were made for each 1-gal sample that was to be used in that experiment. The determinations were made using 1-ml samples withdrawn from the 1-gal containers after thoroughly mixing the sewage sludge. Each 1-ml sample was injected into a preweighed crucible containing a glass-fiber filter. The liquid was pulled through the filter by suction. The crucible was heated to 82^{o} C for 1 hour. The crucible was reweighed after cooling and the total suspended solids in grams per liter were calculated for the sample.

To prepare for an experiment, the water tank was filled to within 0.3 m of the top with 11 600 liters of water. Conditioned tap water (filtered and deionized) was used in the tank for two of these experiments. Water from Back River was pumped directly into the tank without conditioning for the other experiment. Sewage sludge was mixed with the water in each case to obtain concentrations of 4.3, 17, 34, 69, and 80 ppm. These concentrations were selected to cover the range believed to exist in plumes several minutes after an ocean dumping operation occurs. The tap water contained less than 0.5 ppm suspended solids and less than 2 ppm dissolved substances after being conditioned through the filtration and deionization system. Water from Back River, however, contained

3.1 ppm suspended solids and 15 000 ppm dissolved substances. Total suspended solids for these tests included sewage-sludge concentrations plus those of the base water.

After the tank was filled, the circulation system was activated and the water was allowed to circulate until a steady-state condition existed in the tank. During this period, a radiance spectrum of a standard neutral test gray card (gray side, 18 percent reflectance) was measured with the test card placed near the surface of the water. The data obtained from this card were used to normalize the sewage-sludge radiance spectra so that spectral differences were more easily recognized. The test card had a flat spectral response between 360 and 690 nm so that 18 percent of the incident solar simulator radiation was reflected in this wavelength range. Above this range, the reflectance gradually increased to 25 percent at a wavelength of 970 nm. A correction was applied to account for this increase before these data were used in the normalization procedure.

Following the test-card measurements, an upwelled radiance spectrum for the base water was obtained. Then the proper amount of sewage sludge was mixed with the water to achieve a sewage-sludge concentration of 4.3 ppm. This mixture was again allowed to circulate for a period of time until the sewage sludge was evenly distributed throughout the tank, and an upwelled spectrum was measured as before. Additional sewage sludge was added until the sewage-sludge concentration was 17 ppm. This procedure was repeated to obtain upwelled spectra for the other concentrations. Generally, after the water tank was filled, 2.5 to 3.0 hours were required to complete an experiment. Differences in the experiments were minimized so that cursory effects of base water could be evaluated and an indication of repeatability obtained.

RESULTS AND DISCUSSION

Upwelled radiance distributions with wavelength for the three experiments are shown in figure 3 for the base waters and for sewage-sludge concentrations of 4.3, 17, 34, 69, and 80 ppm. Conditioned tap water (table I) was used as the base water for the experiments conducted on October 28 and November 9 (figs. 3(a) and 3(b)), whereas Back River water (table I) was used as the base water for the experiment conducted on November 4 (fig. 3(c)). Data at some wavelengths for concentrations of 34 and 69 ppm in figure 3(b) and 4.3 ppm in figure 3(c) were not obtained. The trends, however, may be surmised from the other curves presented. The spectrometer system spectral resolution for these experiments was 32 nm. The error due to hand readout of the data was estimated to be $\pm 2.9 \times 10^{-6} \frac{\text{mW/nm}}{\text{cm}^2\text{-sr}}$. The absolute accuracy of the radiant power measurements based on the manufacturer's spectrometer specifications is ±20 percent between wavelengths of 400 and 600 nm and ±12 percent between 600 and 967 nm. Included in the absolute error is a repeatability uncertainty of ±13 percent between 400 and 600 nm

and ±3.5 percent between 600 and 967 nm. Discussions with a representative of the manufacturer of the instrument indicate that these values represent 3-sigma error bands. Based on the data presented in figure 3(a), these errors introduce an uncertainty of $\pm 12.4 \times 10^{-6} \frac{mW/nm}{cm^2\text{-}sr}$ at the maximum value for the 4.3-ppm ($\lambda \approx 480$ nm) curve and $\pm 51.1 \times 10^{-6} \frac{mW/nm}{cm^2\text{-}sr}$ at the maximum value for the 80-ppm ($\lambda \approx 599$ nm) curve. These errors are equivalent to an absolute error of ±20 percent, which indicates that the hand readout error is negligible. The hand readout error, however, should not be ignored when considering a specific spectrum (for a concentration of 34 ppm, for example) and the variations occurring in that spectrum which define the spectral signature. Based on the data presented in figure 3(a), the hand readout error introduces an uncertainty of ±5 percent at the maximum value for the 4.3-ppm curve and ±1 percent at the maximum value for the 80-ppm curve. The abrupt spectral variations in these curves near 600 nm and between 750 and 950 nm are believed to be caused by the light source and other factors not related to the spectral response of the sewage sludge.

Figure 4 shows the reflectance distributions with wavelength. Reflectance is presented as a percentage of the radiance entering the water as determined from the test-card measurements. Data for the sewage sludge in conditioned tap water (October 28 and November 9) are presented in figures 4(a) and 4(b) and in Back River water (November 4) in figure 4(c). Notice that the abrupt spectral variations seen in figure 3 near 600 nm and between 750 and 900 nm are not seen in these figures. The results of figure 4 show only slight variations in the reflectance with wavelength for a particular concentration. Reflectance increased with increasing concentration at all wavelengths. Generally, for all concentrations, the reflectance decreased with increasing wavelength with a minimum value occurring near 750 nm. There were no prominent features (peaks or valleys) at any wavelength for any of the concentrations. However, reflectance values were measured for all wavelengths and concentrations considered. The level (magnitude) of the curve for each concentration was well defined and different from the curves for other concentrations. The variation of reflectance with wavelength is fairly consistent for wavelengths less than 800 nm for all concentrations. Beyond 800 nm, however, the data measured on November 9 (fig. 4(b)) show reflectance increasing as wavelength increases for most concentrations. This trend is also evident in figure 4(c) (November 4), although this comparison should be made with some reservations since the base waters are different. Additional comparisons of these data are made in figures 5, 6, and 7.

Figure 5 shows a comparison of the reflectance values measured on October 28 with those measured on November 9 at the wavelengths indicated in the figure. Also, groups of points are identified with the concentration for that set of points, and alternate

concentrations are shaded to help distinguish sets. The base water for these experiments was conditioned tap water. Figure 6 shows a similar comparison of data measured on October 28 (fig. 6(a)), and November 9 (fig. 6(b)) with data measured on November 4 when the base water was taken from Back River. For perfect agreement, all points would fall on the 45° line. Scatter of the points in a set along the agreement line indicates the variation of radiance values with wavelength for that concentration, whereas displacement from the line shows how the radiance measurements agree in magnitude for the two experiments.

In figure 5, comparisons of reflectance for sewage-sludge concentrations of 34 ppm and less and wavelengths less than 800 nm indicate good repeatability results for these two tests. The largest dispersions from the agreement line occur for wavelengths greater than 800 nm and may be due to the smoothing procedure used to smooth out the variations in the normalized data caused by the xenon peaks in the light source. Dispersions may also occur due to readout errors, but these would be small (<5 percent). Comparisons for concentrations greater than 34 ppm (69 and 80 ppm) are not as good, however, and the dispersions are probably due to an error in estimating the mixture concentrations for the October 28 experiment. Reflectance values for October 28 for concentrations greater than 34 ppm are consistently lower than the values for November 9 for all wavelengths, and suggest the possibility that the actual concentrations of sewage sludge in the tank were lower than estimated. These data indicate satisfactory repeatability results for concentrations of 34 ppm and less, but additional tests are needed to confirm this result for concentrations greater than 34 ppm.

Less agreement is shown between the data measured in conditioned tap water (October 28 and November 9) and the data measured in Back River water (November 4) as shown in figure 6. The base water from Back River contained 3.1 ppm suspended solids, whereas the conditioned tap water contained less than 0.5 ppm. The reflectance values for the Back River data are higher, as expected. This trend might be expected to occur for other sewage-sludge concentrations since the Back River water had suspended solids plus other materials in it. Reflectance values, however, for the Back River base water (3.1 ppm) and for sewage sludge in conditioned tap water (4.3 ppm) are essentially the same. This is best observed by comparing figures 4(a) and 4(b) with figure 4(c). Also, reflectance values at concentrations of 17 and 34 ppm are essentially the same regardless of the type of base water. At the higher concentrations, however, reflectance values are lower for the Back River water data (fig. 7). These results suggest that the spectral reflectance values could have been influenced by the type of base water. The differences, however, are small, especially for concentrations of 34 ppm and less. At the higher concentrations, 69 and 80 ppm, since the reflectance values were less with Back River base water, this could suggest a physical or chemical process occurring in the natural water at the higher concentrations that did not occur in the conditioned tap water. Additional

experimental tests, however, would be required to clarify these points. No significant variations in the reflectance spectra curves were observed as indicated by the data presented in figure 4.

Figure 7 shows approximated straight-line variations of the reflectance as a function of total suspended solids concentration for several wavelengths ranging from 420 to 900 nm for the three experiments. Data used for these approximations were obtained from figures 4 and 6, and were used to calculate the coefficients of the linear equation for each wavelength by the least-squares method. Initial concentrations of 0.5 ppm for the conditioned tap water and 3.1 ppm for the Back River water were used and were based on results of laboratory analysis of water samples. These concentrations were added to the sewage-sludge concentrations in figure 4 to obtain the values indicated by the data symbols in figure 7. Correlation coefficients for these straight-line approximations were generally high (>0.9) which indicated that the reflectance variation with concentration could be considered linear between 4.3 and 80 ppm without introducing large errors. This result is important to researchers using remotely sensed data with limited ground-support data.

CONCLUSIONS

Radiance and reflectance spectra for primary-treated sewage sludge were obtained for sewage-sludge concentrations from 4.3 to 80 ppm and wavelengths from 420 to 970 nm. Based on the results of these laboratory experiments, the following conclusions were drawn:

1. Reflectance increased with increasing concentration at all wavelengths. At each concentration, reflectance decreased slightly as wavelength increased, with a minimum reflectance occurring at about 750 nm.

2. No significant variations (peaks or valleys) were observed in the reflectance spectra at any wavelength for any of the concentrations.

3. The reflectance may be considered to increase linearly with concentration at all wavelengths between 4.3 and 80 ppm without introducing large errors.

4. The spectral reflectance values appeared to be influenced by the type of base water, but this influence was small, especially for concentrations of 34 ppm and less.

5. Repeatability was good, based on comparisons of similar water-tank tests, for concentrations of 34 ppm and less.

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October 14, 1977

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TABLE I.- CHARACTERISTICS OF BASE WATER

	Conditioned tap water	Back River water
Total suspended solids, ppm	≈0.5	3.1
Chlorophyll a, μg/liter	0	10
Dissolved substances, ppm	<2	15 000

TABLE II.- TYPICAL RESULTS OF LABORATORY ANALYSIS OF PRIMARY-TREATED SEWAGE SLUDGE

Salinity, ppt	2.8
Total suspended solids, ppm	30 000
NO_3, ppm	20.1
PO_4, ppm	15.2
Fe:	
Soluble, ppm	37.5
Insoluble, ppm	40
Pb:	
Soluble, ppm	20.1
Insoluble, ppm	10
Zn:	
Soluble, ppm	20.02
Insoluble, ppm	8
Al:	
Soluble, ppm	2
Insoluble, ppm	80

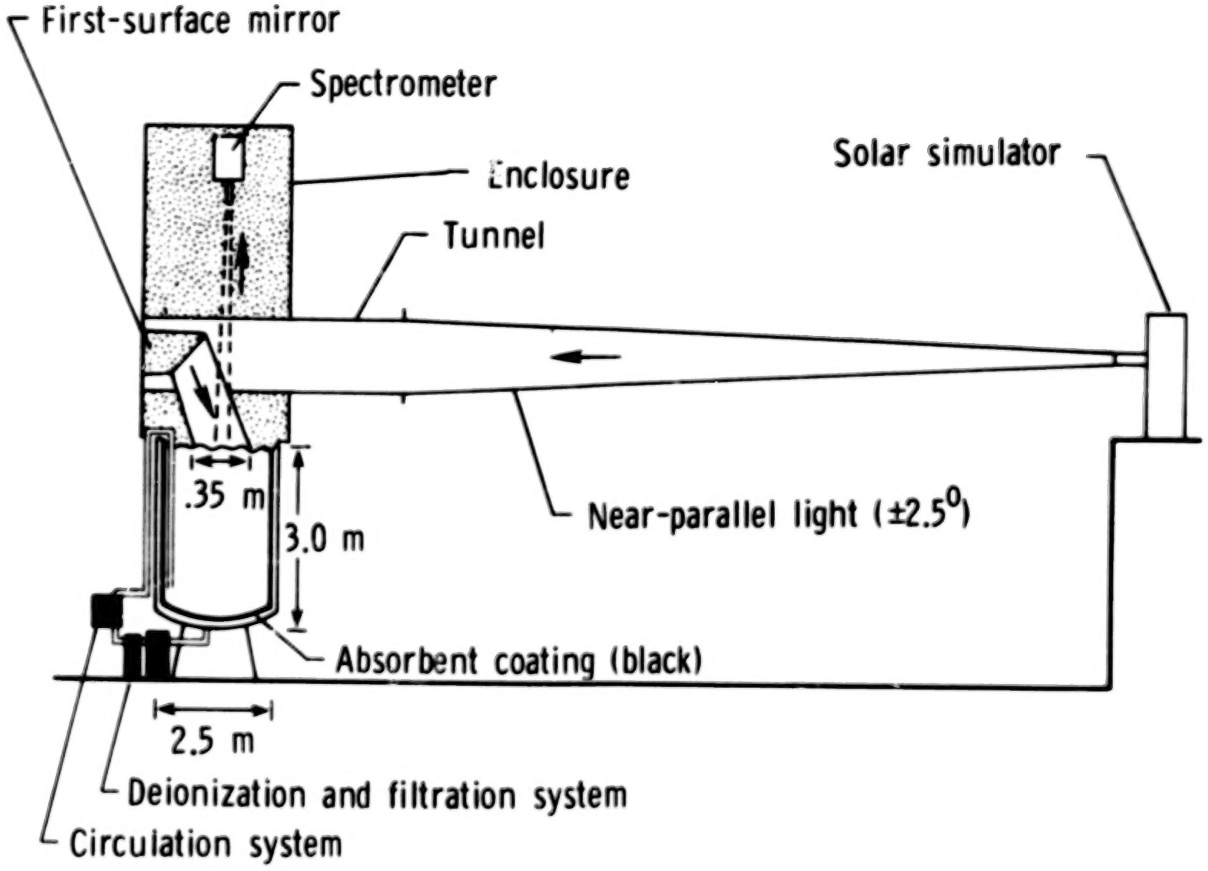
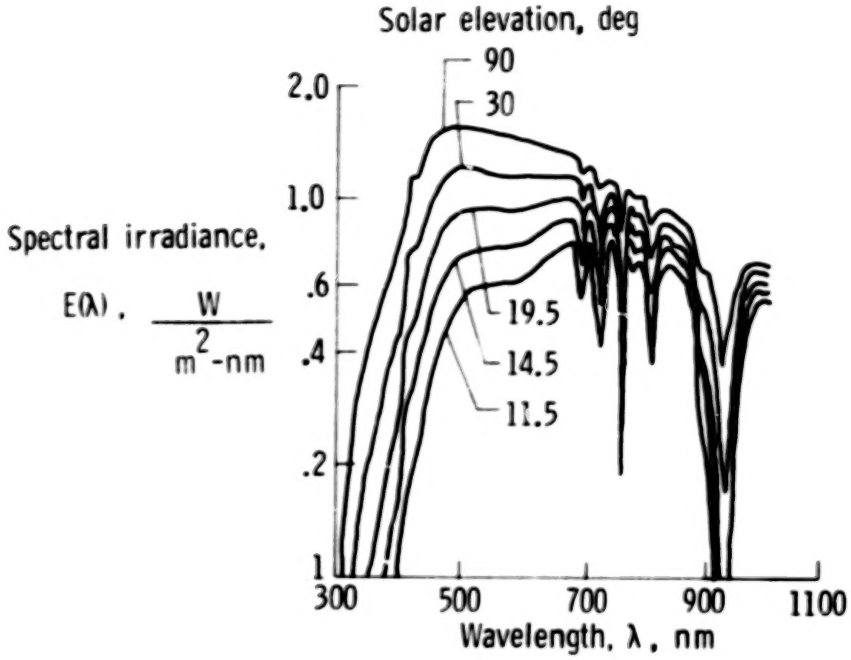
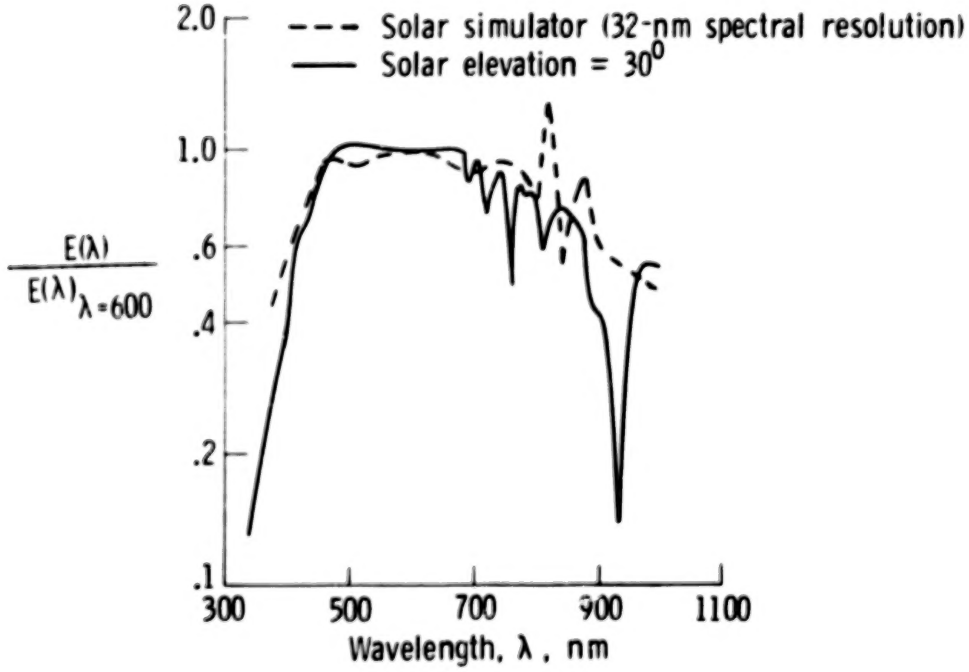


Figure 1.- Sketch of laboratory setup.

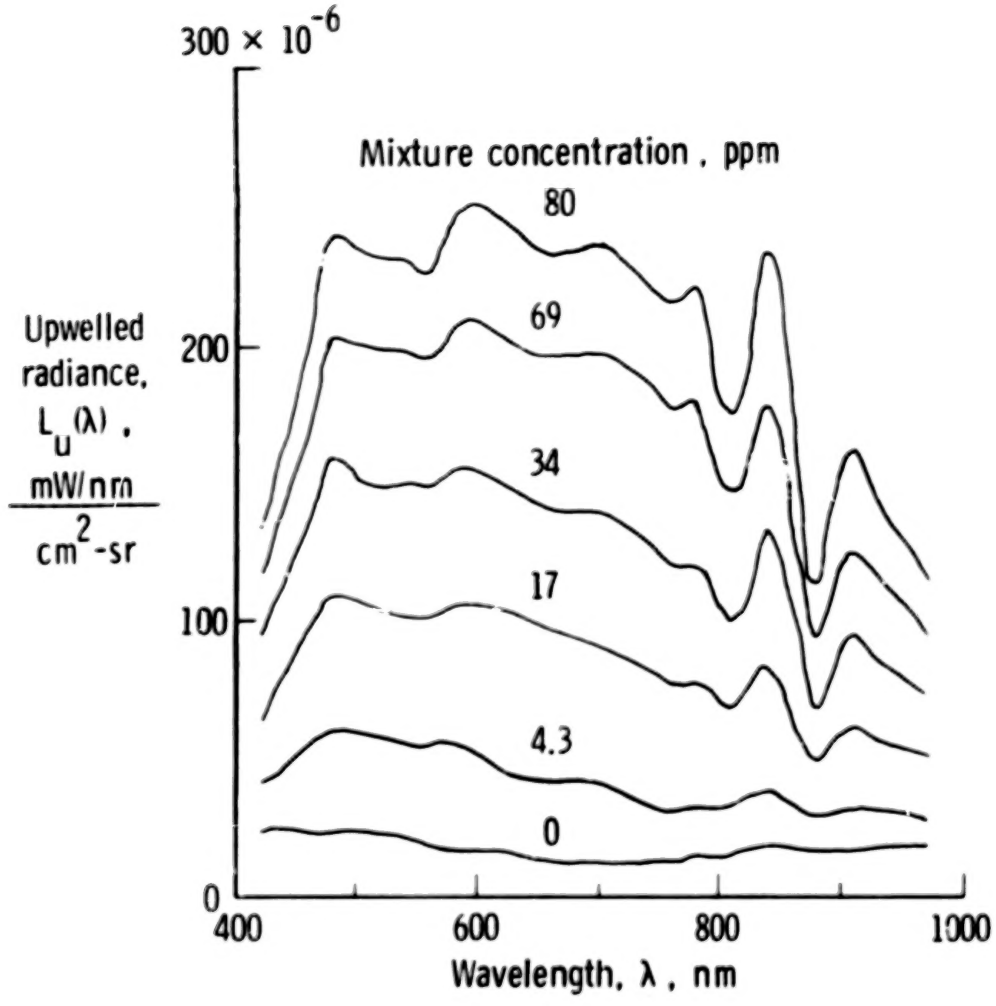


(a) Standard sea-level solar irradiance spectra (ref. 9).



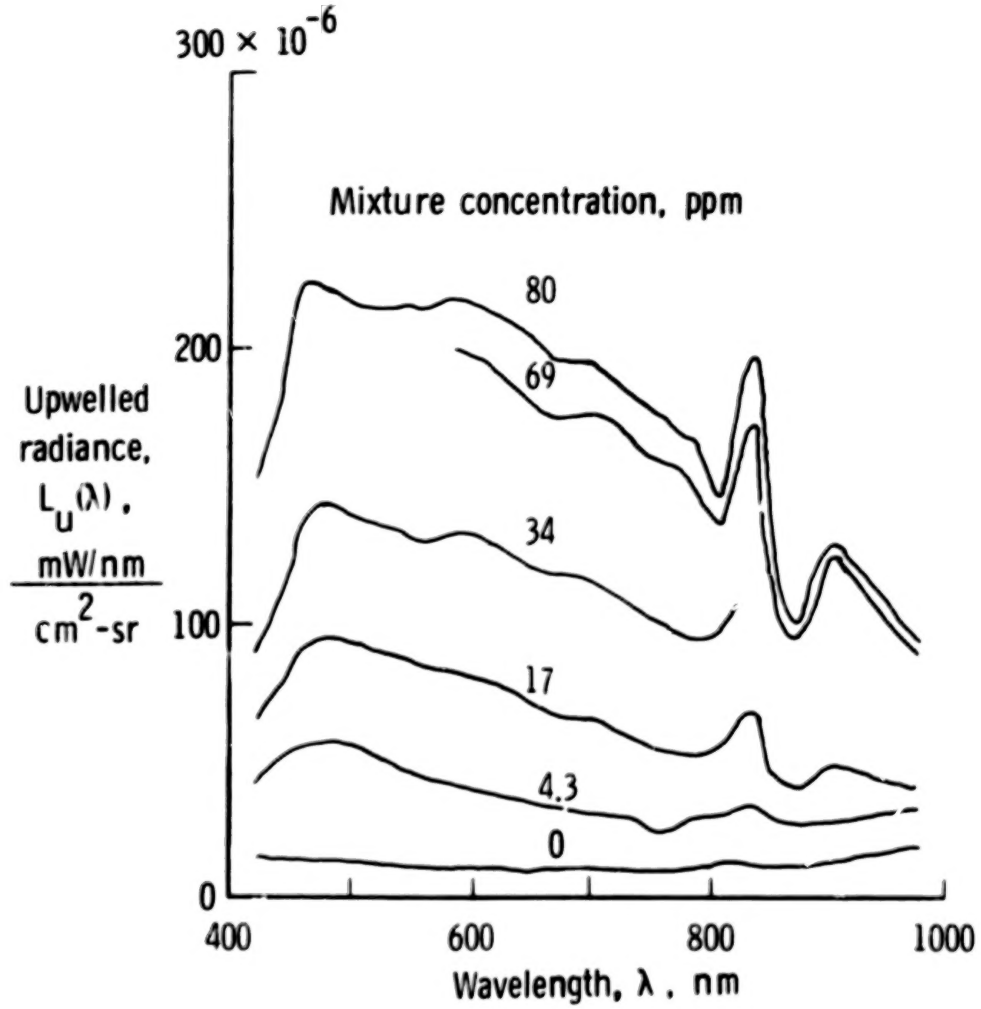
(b) Solar simulator and standard sea-level spectra.

Figure 2.- Standard sea-level solar irradiance spectra and comparison with solar simulator data.



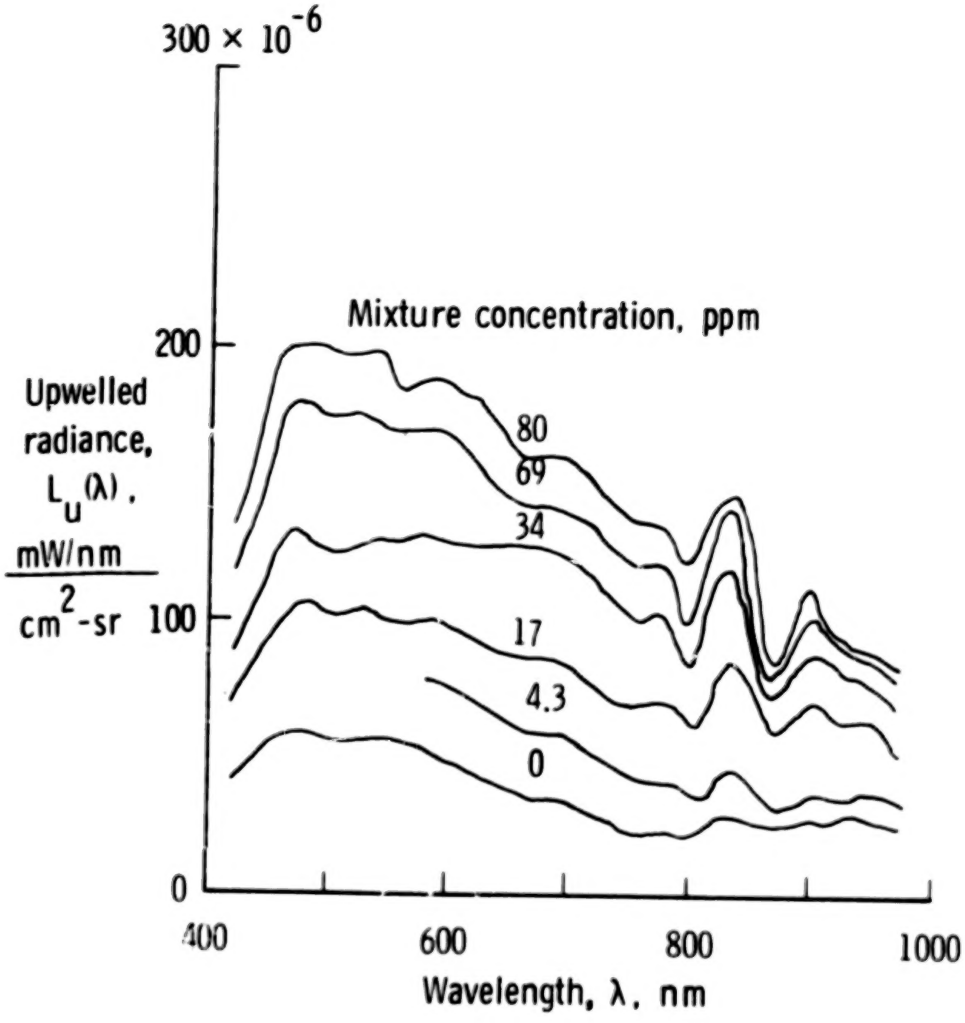
(a) Conditioned tap water as base water: October 28, 1976.

Figure 3.- Upwelled radiance plotted against wavelength. Spectral resolution, 32 nm.



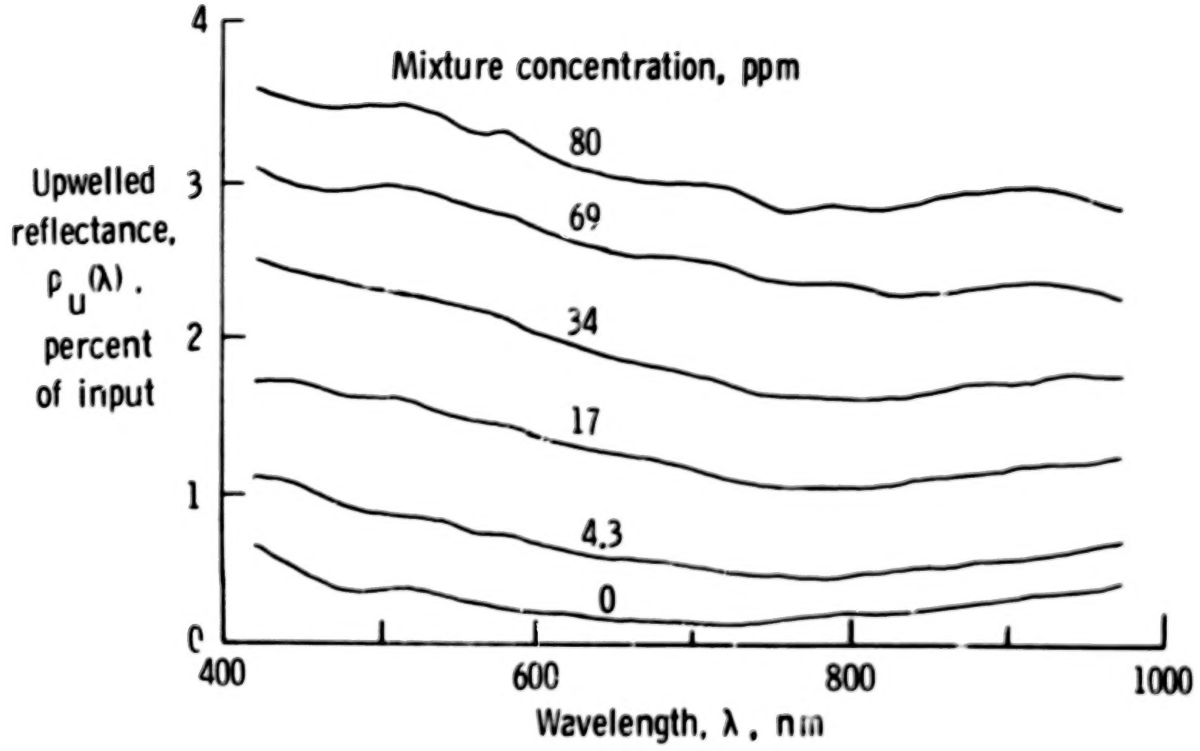
(b) Conditioned tap water as base water: November 9, 1976.

Figure 3.- Continued.



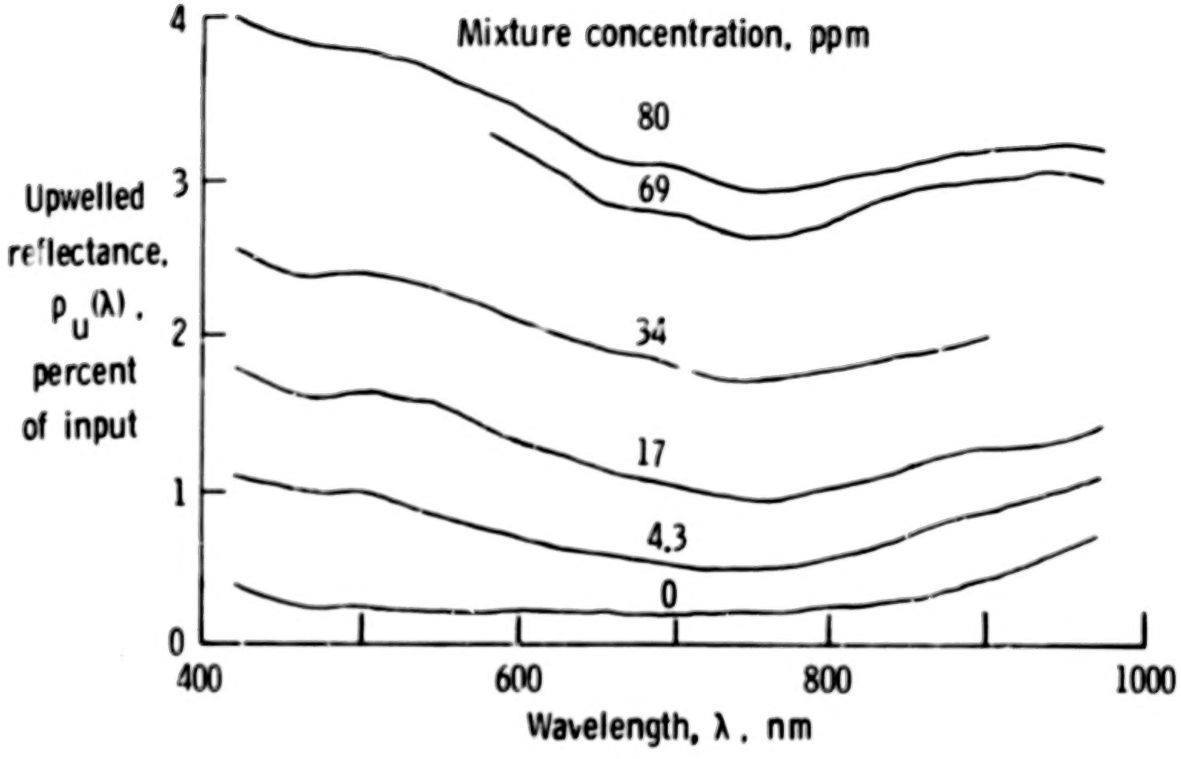
(c) Back River water as base water: November 4, 1976.

Figure 3.- Concluded.



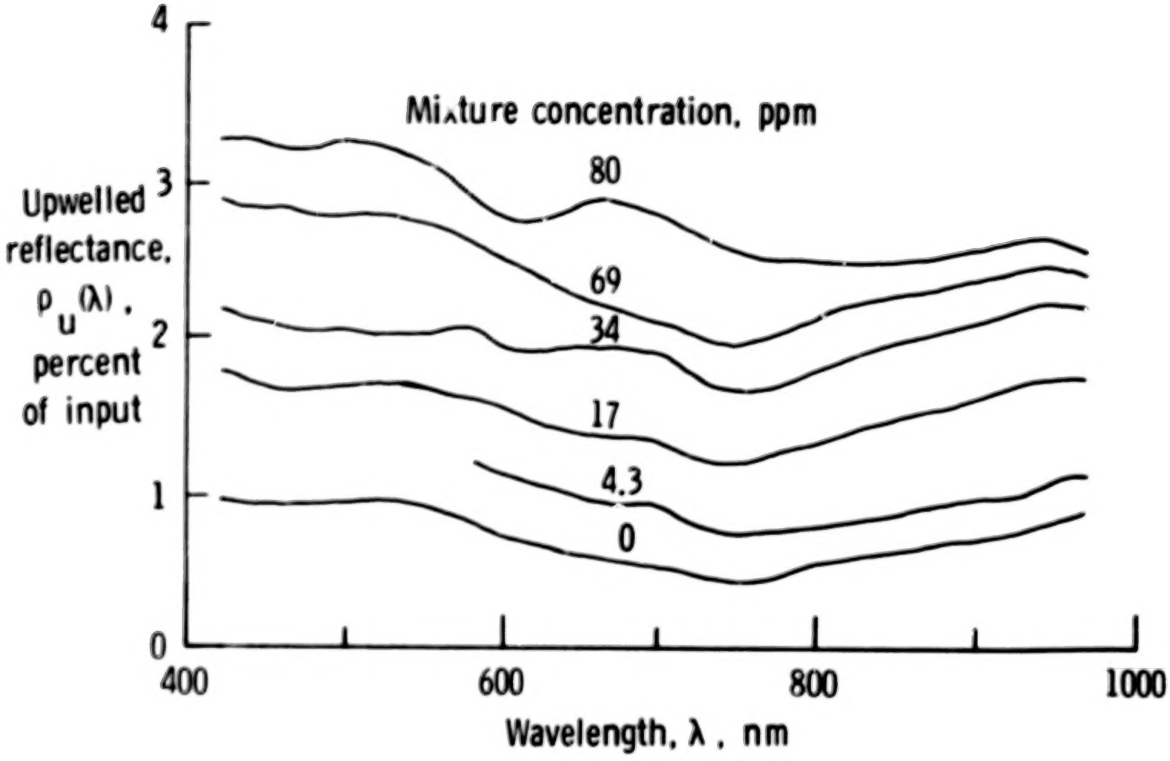
(a) Conditioned tap water as base water: October 28, 1976.

Figure 4.- Upwelled reflectance plotted against wavelength. Spectral resolution, 32 nm.



(b) Conditioned tap water as base water: November 9, 1976.

Figure 4. - Continued.



(c) Back River water as base water: November 4, 1976.

Figure 4. - Concluded.

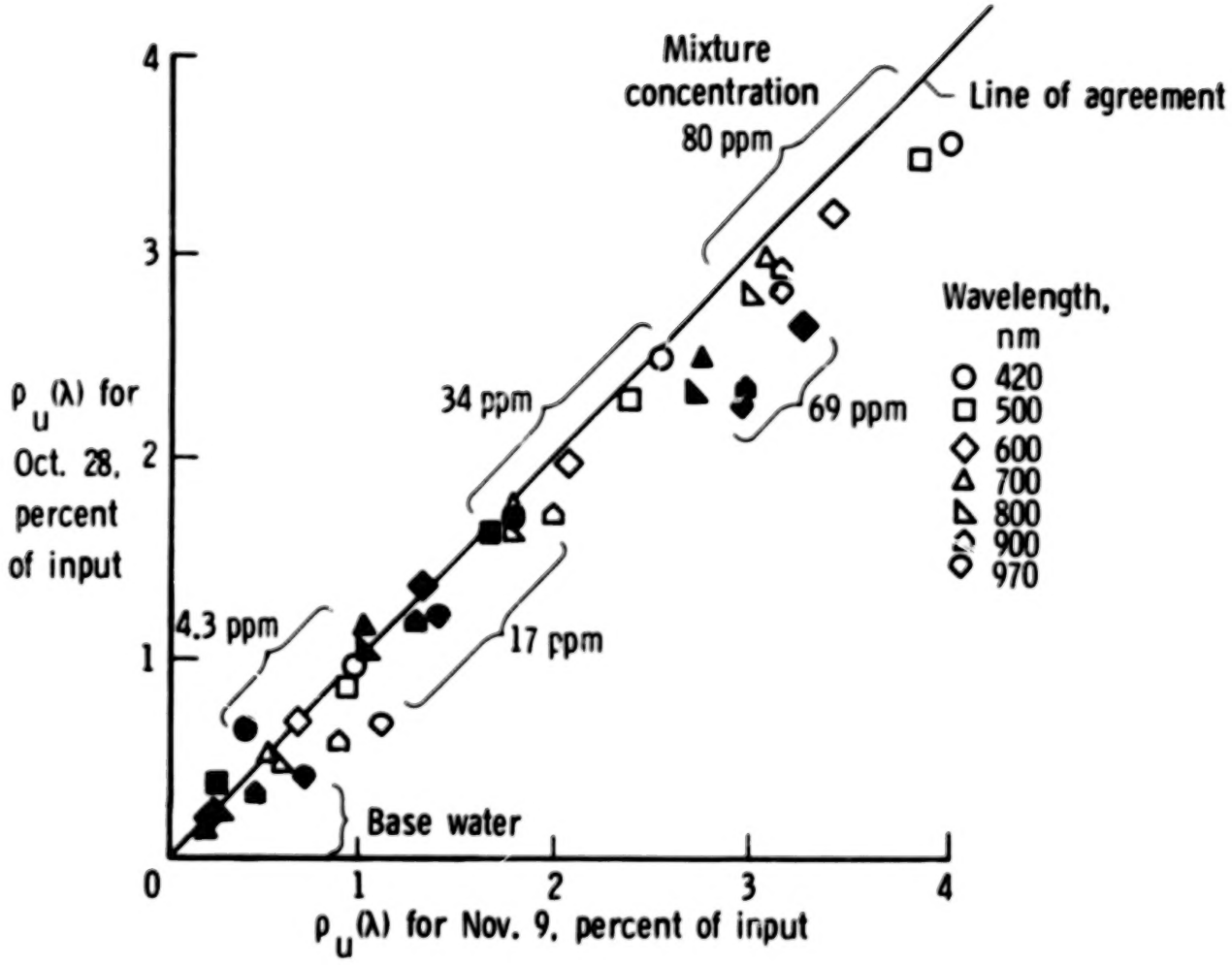
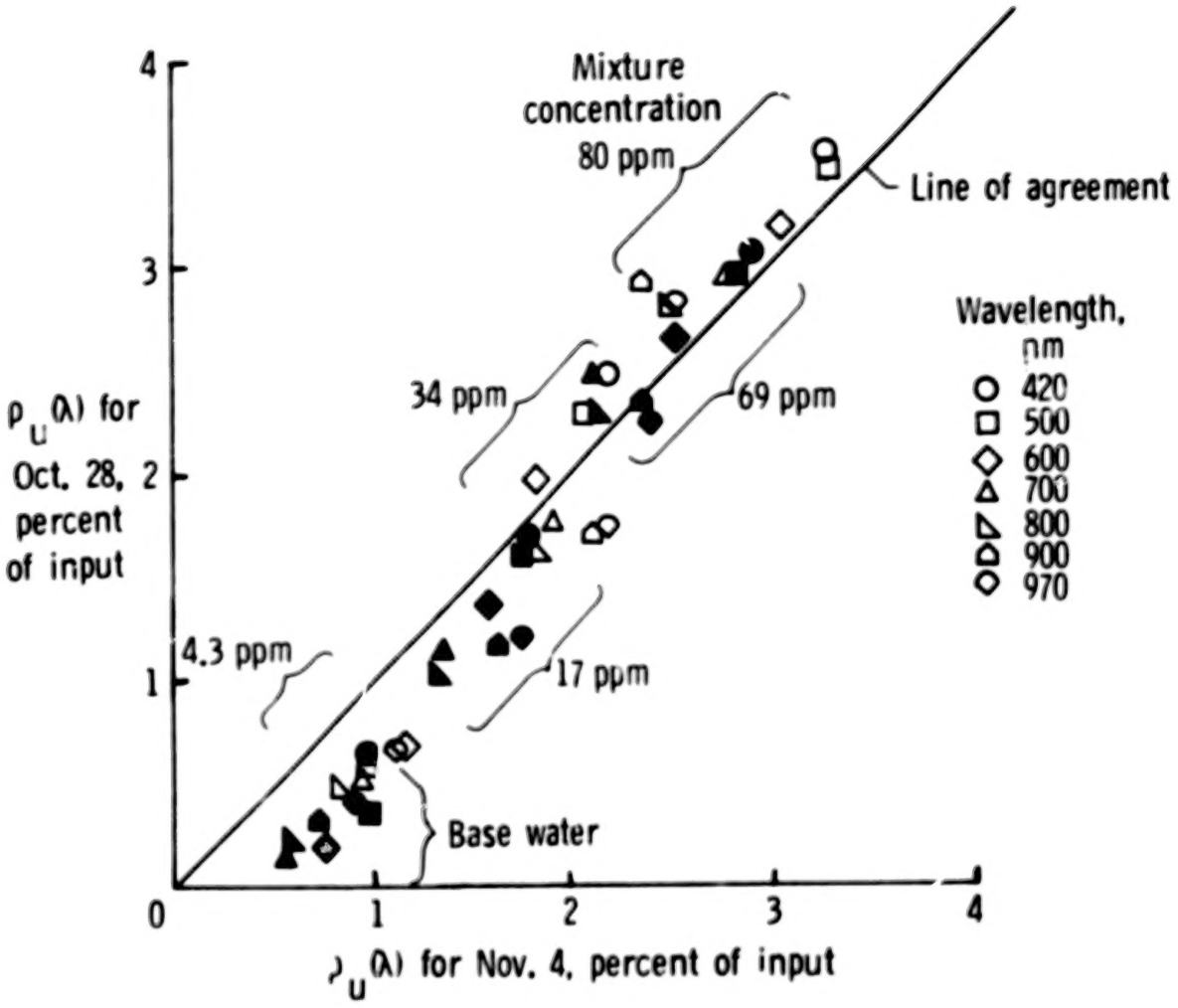
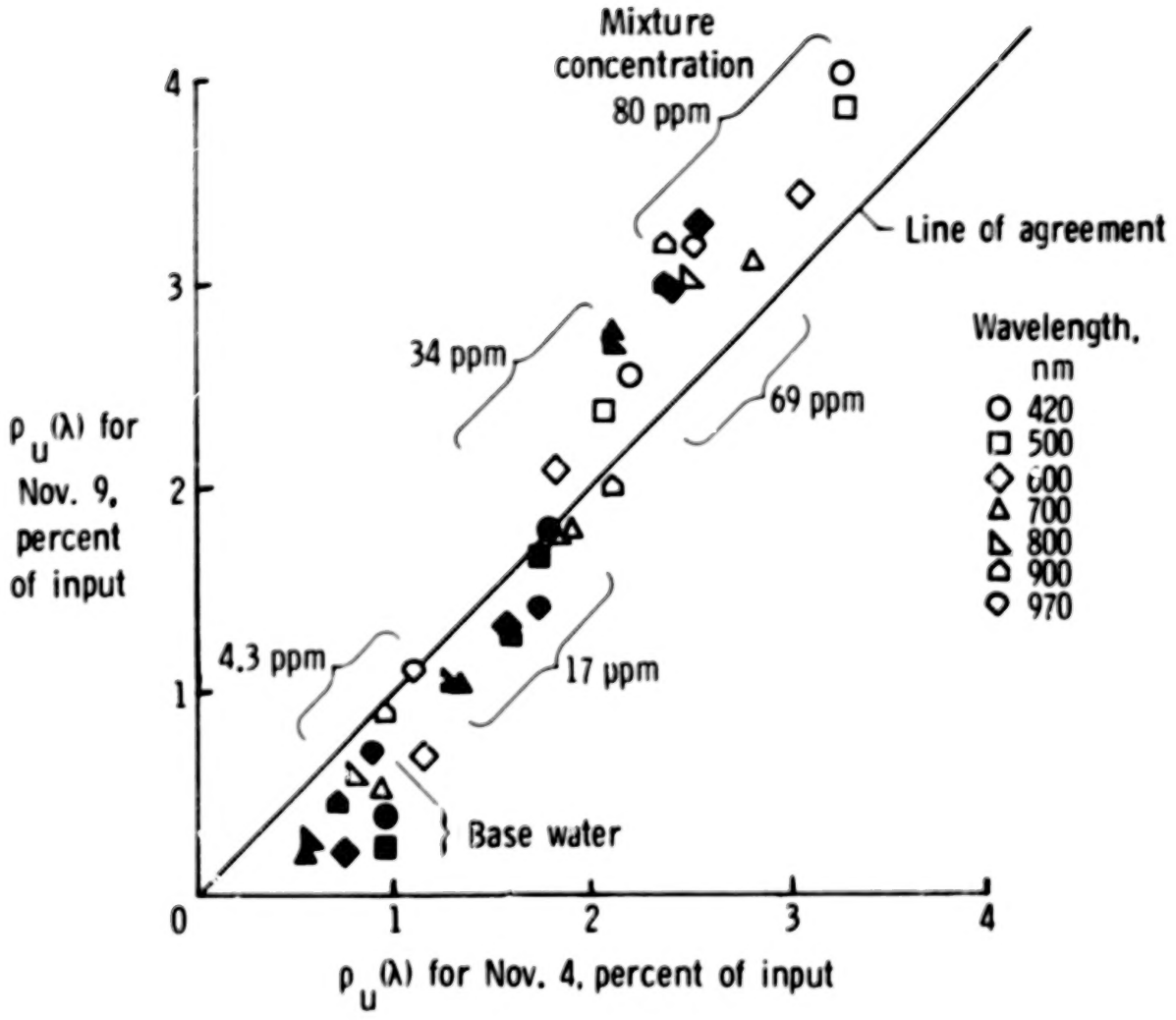


Figure 5.- Comparison of reflectance data for October 28 with data for November 9, 1976. Base water was conditioned tap water. Note that data symbols are shaded for alternate concentrations.



(a) October 28 and November 4.

Figure 6.- Comparison of reflectance data for conditioned tap water (October 28 and November 9) with data for Back River water (November 4). Note that data symbols are shaded for alternate concentrations.



(b) November 9 and November 4.

Figure 6.- Concluded.

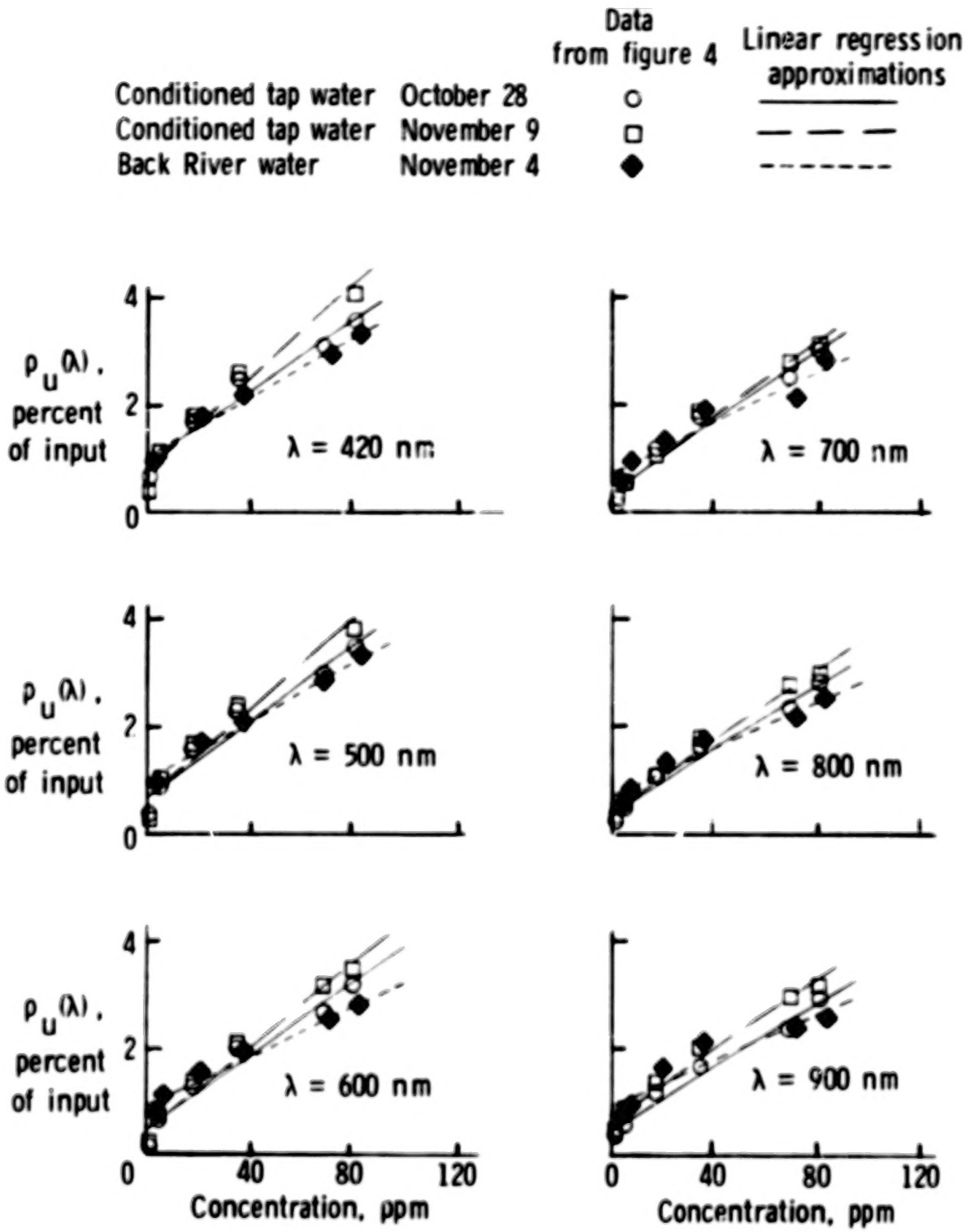


Figure 7.- Comparison of reflectance data for three experiments and approximated linear variations with concentration.

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15. Supplementary Notes

16. Abstract

The National Aeronautics and Space Administration (NASA), in cooperation with the Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA), is conducting a research program to evaluate the feasibility of remotely monitoring ocean dumping of waste products such as acid and sewage sludge. One aspect of the research program involves the measurements of upwelled spectral signatures for sewage-sludge mixtures of different concentrations in a large-scale laboratory. This paper describes the laboratory arrangement, solar simulator, and test results from three experiments conducted in the laboratory. Radiance and reflectance spectra are presented for primary-treated sewage sludge mixed with two types of base water. Results indicate that upwelled reflectance varies in a near-linear manner with concentration and that the sludge has a practically flat signal response between 420 and 970 nm. Well-defined upwelled reflectance spectra were obtained for the sewage-sludge mixtures at all wavelengths and concentrations. The spectral reflectance values appeared to be influenced by the type of base water, but this influence was small, especially for the mixtures with low concentrations of sewage sludge.

17. Key Words (Suggested by Author(s))

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